Numerical simulations of some possible fire scenarios in a closed car park with RANS and LES

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1 Introduction

Prior to any CFD ('Computational Fluid Dynamics') calculation of a fire in a car park, a realistic fire scenario must be provided as input data. With this scenario, CFD results allow the evaluation of several characteristics of the performance of a smoke and heat control system, including:

- effective limitation of the propagation of smoke (and heat) in the car park;
- effective creation of a smoke-free access route from the public road on the fire storey for fire fighters to approach the fire source, i.e. facilitation of active fire suppression.
- the pressure difference created by the smoke control system in the car park, which should not exceed 60Pa for the sake of opening doors.

This paper presents CFD calculation for some possible fire scenarios. We do not consider the possible phenomenon of fire spread in the car park. Rather, we impose a localized fire, modeled as a heat source.

2 Design fire scenarios

A fire can be defined as undesirable burning of materials, with release of heat and toxic gases, causing hazards to people and the structure. A design fire can be defined as a quantitative description of presumed fire characteristics within a design fire scenario. Typically this is an idealized description of the temporal evolution of important fire variables, such as heat release rate, fire source area and shape, etc., along with possible other important input data for modeling such as fire load density [1].

The design fire scenario allows a deterministic fire safety engineering analysis. As the number of possible fire scenarios can be very large, it is necessary to select the most important scenarios for analysis.

Interestingly, there is a discrepancy in the terminology 'fire scenario' in various standards and literature. In [2] a fire scenario is a program for putting into fire configuration one or more smoke control and other fire safety systems, assigned to a detection zone, in the event of a fire. In [3] a fire scenario is a generalized, detailed description of an actual or hypothetical, but credible, fire incident. Such scenarios identify chains of events leading to deaths and other fire losses.

As a consequence, in the literature, depending on the scope of the document the term 'fire scenario' stands for one or several statements of the above definitions [4-6]. In our context we adopt the definition of ISO [1]. Therefore, in the present document, `fire scenario` is a description of the ignition and fire growth process, the fully developed stage, and the decay stage. In the case of car parks the fire scenario in this sense is a function of many parameters, among which: the fact that the car park is open or closed; the possible presence of sprinklers (in combination with a floor with slope; the fuel allowed; the material composition of the cars; …

It is also necessary first to identify the design objectives and criteria of the problem at hand. Three aspects can be considered, regarding the fire protection of the car parks: heat control, smoke control and possible effects on the structure. The choice of priority in these aspects is important for the design purpose. For example, in some Japanese designs, the control of toxic species in the event of fire is the base for the design of fire protection system [7], whereas in other designs, heat control has the first priority.

In the present paper, we focus on smoke and heat, starting from a prescribed fire curve at a well-defined location (see below).

3 Design fire

The chosen design fire prescribes the location of the fire, its size (possibly changing in time) and its heat release rate (also possibly changing in time). In principle, the 'worst case' position must be aimed at. In the present study, the geometry is very simple and we put the car on fire in the middle of the car park.

In our study, we only focus on the first stages of the fire (fire growth and briefly a fully developed state). We do not consider the decay stage, in order to save computing times. We make use of data, available from tunnel fire studies [4-6]. Basically, there are three types of heat release curves: linear evolution (linear growth and decay, with a steady phase in between); quadratic growth and exponential decay (with steady phase in between); and exponential growth and decay. We choose a linear curve, where the maximum heat release rate (set here to 4MW) is reached after 5 minutes (t_{max} = 300s). We compute another 5 minutes with this maximum heat release rate.

Note that a study of car park fires has recently been completed by BRE (UK). The publication of the report is expected in the near future. Obviously, the results of this study might offer a better quantification of the design fire for modern cars in a car park.

4 Numerical simulation results

The general objectives of the simulations have been outlined in the introduction. Results are presented as obtained with OpenFoam [9] with RANS and LES turbulence modelling. FDS [10] LES results are presented as well.

4.1 Model description

A schematic model of a closed car park is shown in Fig. 1. This model is consistent with the construction for experimental investigations at WFRGent NV (Ghent, Belgium).

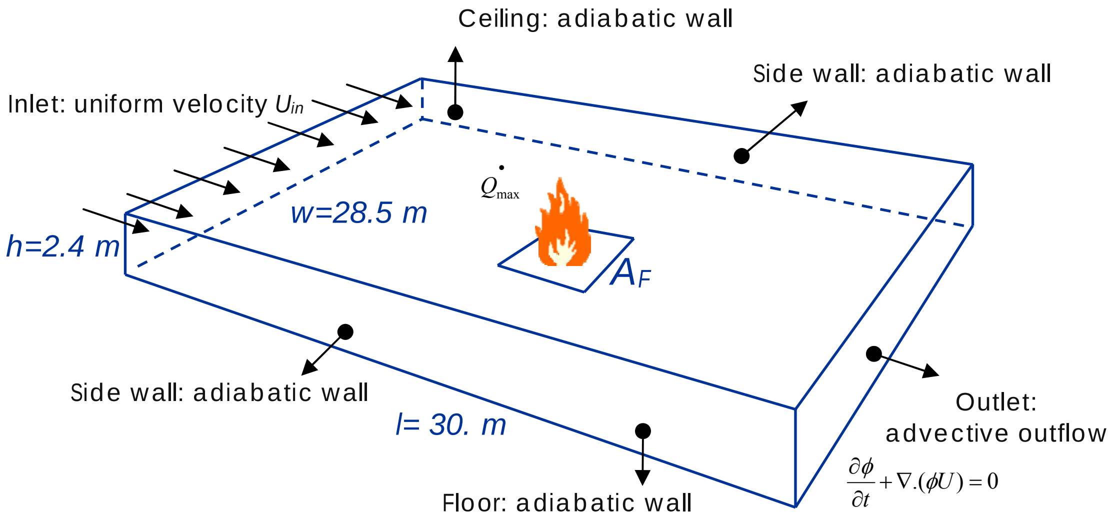


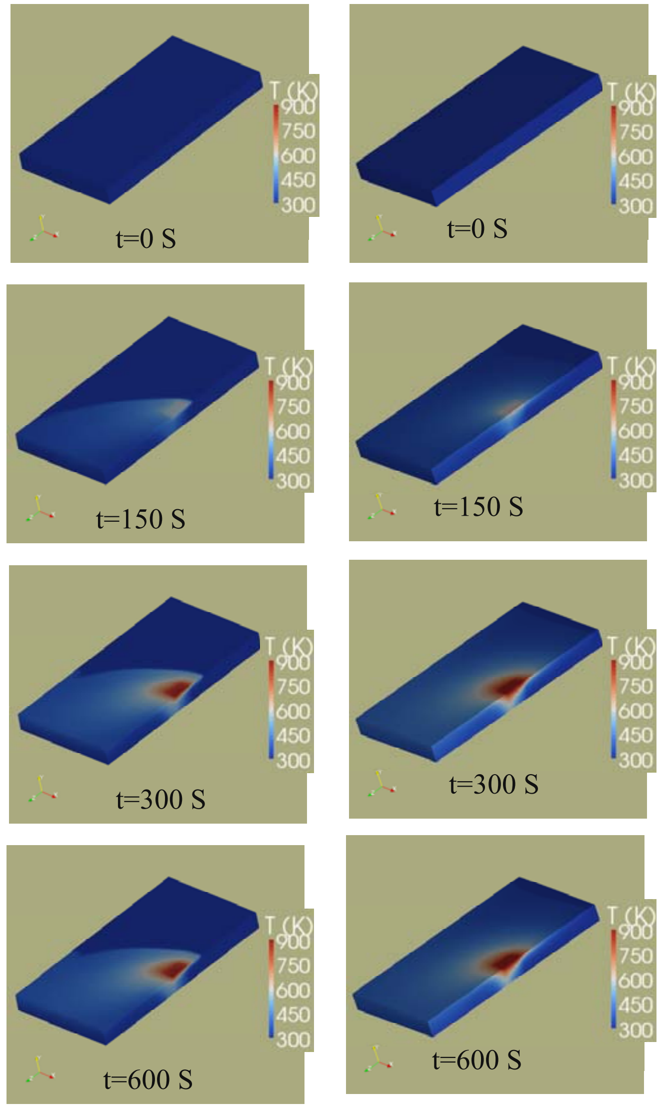
Fig. 1. Schematic model of the closed car park.

The height, width and length of the car park are 2.4m, 28.5m and 30m. The fire size is A_F= 3×3m^2. The ventilation system is modeled as a uniform inlet velocity. At the outlet, an advective boundary condition is used. This was most feasible in OpenFoam. The extraction rate can be derived from the inlet mass flow rate. The ceiling, floor and side walls are assumed adiabatic. The fire is simulated by insertion of a homogeneous volumetric thermal heat source in the energy equation ($Su_{fire} = \dot{Q}(t)/(A_F h)$, over the entire car park height and with the fire heat release rate as described above). Detailed effects of sprinklers are not considered in the simulations.

4.2 Effect of the inlet velocity

Limitation of the smoke and heat propagation is considered an important objective in the design of the smoke control system. The smoke back-layering length is thus an appropriate indicator for the effectiveness of the system.

Fig. 2 shows temperature distributions during the fire evolution for two different inlet velocities (U_{in}= 1.3m/s (left) and 0.5m/s (right)). The standard k-ε RANS turbulence model [11] is applied. A uniform grid, with cell size 0.2m, was used in the entire computational domain. We take advantage of the symmetry in the configuration and perform the simulations in half of the car park. As expected and in line with the results in [8], the lower inlet velocity leads to an increase in back-layering length. Also, with the lower ventilation velocity, the average temperature in the car park is higher. Yet, we recall that we do not consider fire spread (which might be more rapid and severe under favorable ventilation conditions, see e.g. [12]).



(a) Inlet velocity of U_{in}=1.30 m/s (b) Inlet velocity of U_{in}=0.50 m/s

Fig. 2. Temperature in an empty car park with a fire in the middle; (a) U_{in}= 1.3 m/s; (b) U_{in}= 0.5 m/s. Turbulence: k-ε.

An interesting observation is that, with the settings as they are, the time scale of the flow is much shorter than the time scale of the global fire evolution. Indeed, the difference between the temperature distributions at t =300s and at t = 600s hardly differ. In other words, for the selected heat release curve as described, the response of the flow field to variations in the heat release rate is practically instantaneous. This is interesting, as this implies that the behavior is at all times quasi-steady, i.e. history effects are negligible and the state at each instant can be computed as if it were a steady state. Being an advantage with RANS turbulence models, this is not relevant in LES calculations (which need to be 3D and time accurate anyway to resolve the large eddies). It is well possible that there is a critical growth rate of the fire heat release curve (or, equivalently, a minimum value of t_{max}) below which the flow field can be considered quasi-steady.

4.3 Effect of neighboring cars

The numerical simulations of the previous section were for an empty car park. However, the presence of other cars will change the flow pattern in the car park, and thus also the fire scenario (even if we do not consider fire spread). In this section, we consider the two configurations of Fig. 3, in which three cars parked with a distance of 1m from each other. In both cases, the middle car is on fire. The difference between the two scenarios is the blank space of 4m between the middle car and the car upstream in scenario A. The fire heat release rate evolution is the same as in the previous section.

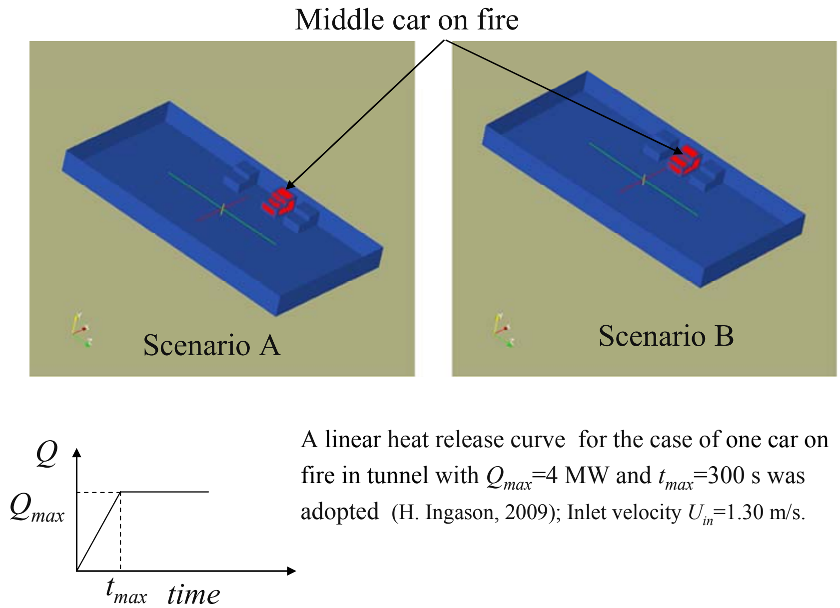
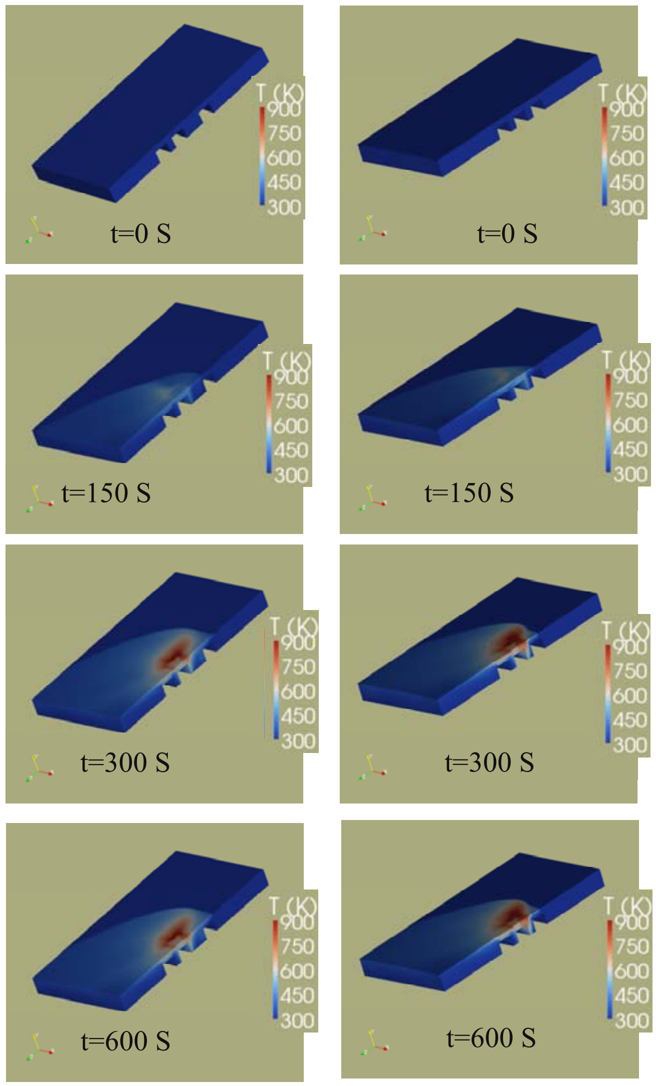


Fig. 3. Schematic of configurations A and B (presence of cars).

Fig. 4 shows the temperature distribution evolution, as obtained with the standard k-ε turbulence model. Due to the presence of the other cars, the temperature distribution remarkably differs from that in the empty car park (Fig. 2). There is more back-layering and there is a complex flow pattern near the car on fire. In configuration A, the blank space leads to a cavity flow between the car on fire and the upstream car. The recirculation in this cavity transfers heat from the car on fire to the upstream car and results in increase of the temperature near the upstream car. Without the blank space, there is no such cavity flow.

4.4 Effect of turbulence model

With the LES technique for turbulence modeling, the turbulent motions can be simulated in more detail. Yet, the grid size must be chosen properly. In [13], Van Maele and Merci proposed to use the k-ε turbulence modeling prior to LES calculations, in order to estimate the turbulent integral length scale l_i and, hence, the required grid sizes for LES. The results suggest that for both the scenario A and B the small scale of l_i is about 0.15m (not shown). Therefore, unstructured grids were generated in OpenFoam with smallest grid size equal to 0.03m and largest grid size 0.25m. The computing time with LES was about 10 times larger than with the k-ε model. The time, keeping the cell CFL number well below unity with, was about 5ms with LES and about 50ms with k-ε.



(a) Scenario A (b) Scenario B

Fig. 4. Temperature distribution with neighboring cars. Left: with blank space (A); right: no blank space (B). U_{in} = 1.30 m/s. Turbulence: k-ε.

Fig. 5 shows the temperature distribution in the case of scenario A. The results look qualitatively very similar. Of course, with LES some unsteadiness is captured. The maximum temperature with LES (around 900K) is about 100K higher than obtained with k-ε. There is also somewhat more pronounced back-layering in the LES results.

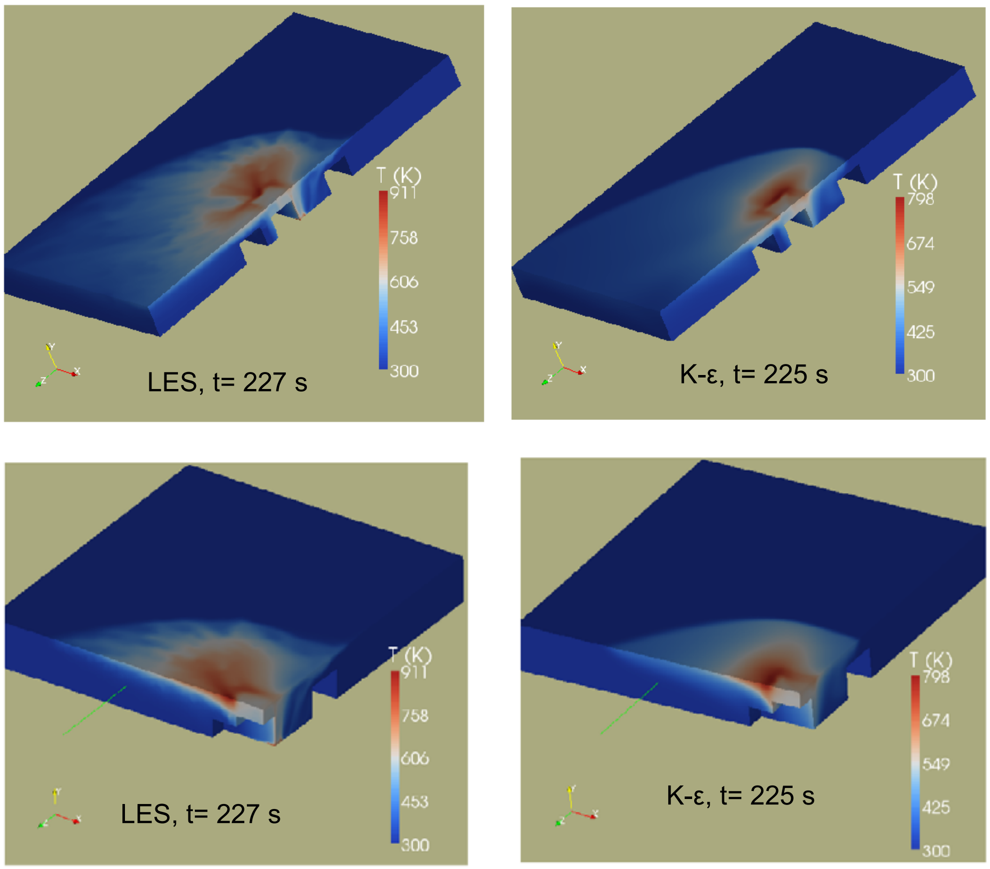


Fig. 5. Effect of turbulence modeling on the temperature distribution of temperature. Left: LES; right: RANS. $U_{in} = 1.30$ *m/s.*

Note that we use symmetry in the LES simulations, even though this is in principle not allowed. Performing calculations for the same configuration for the entire car park (i.e. not using the symmetry condition) revealed that differences in the temperature distributions are negligible.

We now show the importance of the LES grid size, presenting results with the same numerical and modeling settings, but using a different minimum cell size. Due to the spatial filtering, using the mesh itself, grid independence of the results must not be expected. Yet, the differences in Fig. 6 are clear: much of the details are not captured if the grid is not sufficiently fine (right column: uniform Cartesian grids with cell size 0.2m). Using the estimate of the turbulent integral length scale (left column) seems a good approach to truly capture the turbulence unsteadiness. From a qualitative point of view, the distributions are similar, though, albeit that there is more diffusion with the coarser mesh.

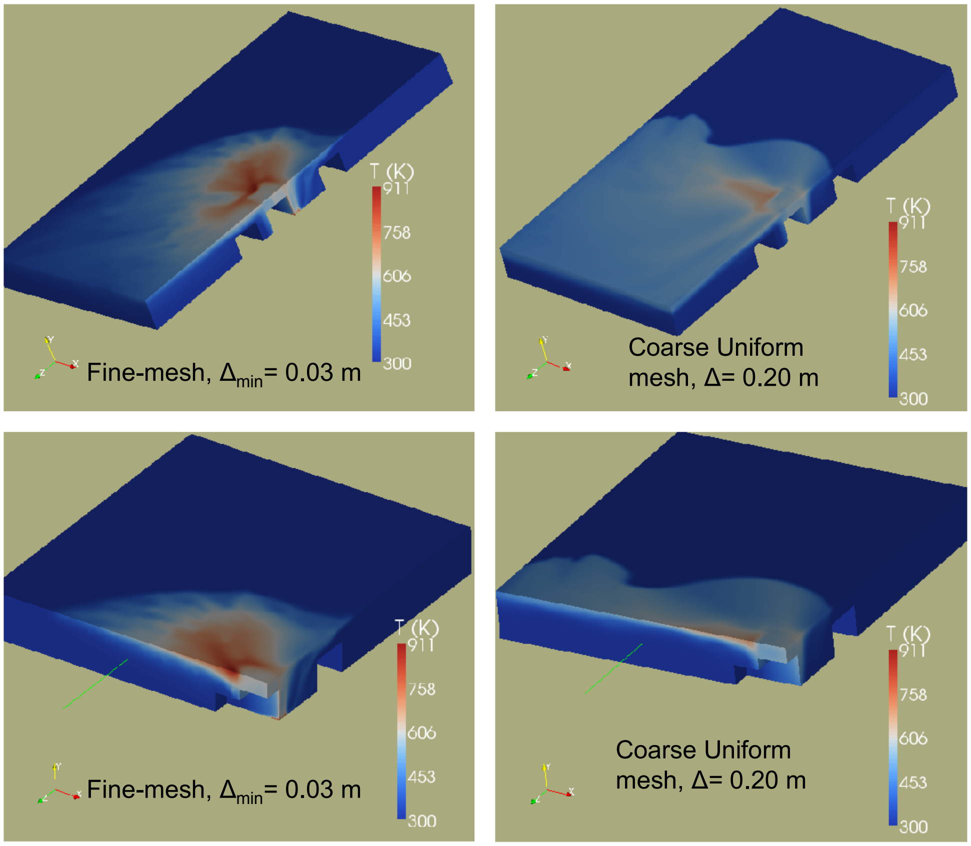
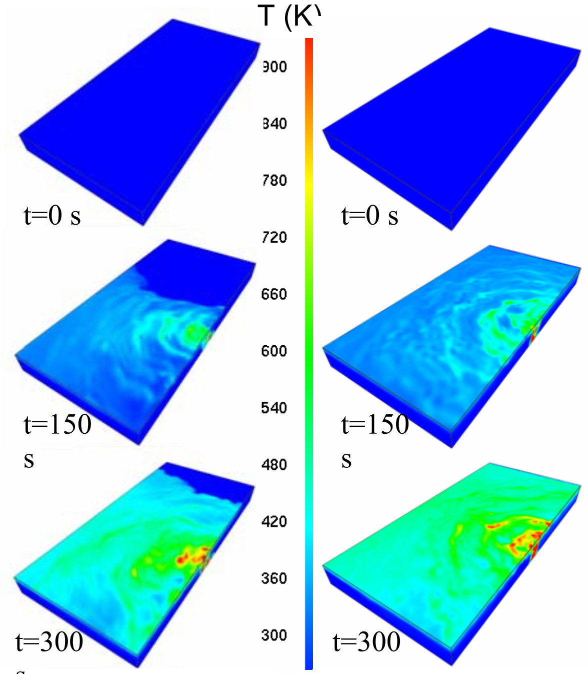


Fig. 6. Effect of grid size on the temperature distribution evolution with LES.

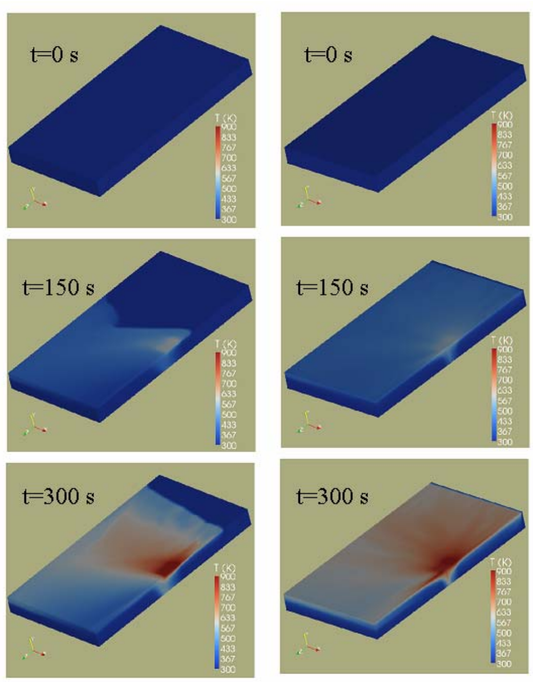
4.5 Fire model

In order to judge the quality of the results with the fire as homogonous volumetric thermal source (as shown so far), we also use a one-step chemical reaction for combustion in the empty car park configuration. The fire is again positioned in the middle and the two inlet ventilation velocities U_{in}= 1.3m/s and 0.5m/s are applied. Fig. 7 shows FDS results and Fig. 8 results with OpenFoam. A uniform Cartesian grids with the cell size 0.2m is used. The general flow dynamics, particularly in the region far away from the fire, are very similar. FDS reveals more unsteadiness in the results, but the global observations are definitely very similar. Note that the OpenFoam LES results do not look similar to the k-ε results of fig. 2, but this may well be due to the grid that might be too coarse (cfr. Fig. 6). Yet, it must also be acknowledged that the k-ε results should not be considered as 'reference' results to estimate the quality of the LES results. Also note that the global picture looks very similar to what is obtained when fire is modeled as a homogeneous heat source in the energy equation. Obviously, detailed observations in the region of the fire source are different, but for the evaluation of the effectiveness of the smoke control system, the volumetric heat source seems an adequate approach.



(a) Inlet velocity U_{in}= 1.3 m/s (b) Inlet velocity U_{in}= 0.5 m/s

Fig. 7. FDS results for temperature in an empty car park with a fire at its middle.



(a) Inlet velocity U_{in}= 1.3 m/s (b) Inlet velocity U_{in}= 0.5 m/s

Fig. 8. OpenFoam results for temperature in an empty car park with a fire at its middle.

5 Conclusions

CFD simulation results were presented for fire in a closed car park, using a prescribed fire scenario of linear increase and steady state heat release rate. Several possible fire scenarios were examined.

First, k-ε results were presented. The effect of the presence of cars on the flow field was discussed. In particular, the possibility of cavity flows was mentioned.

Using the k-ε results for the determination of a suitable minimum grid size for LES calculations [13], seems appropriate. When a uniform, coarser, mesh was used, results are clearly different. On the other hand, the global patterns remain unchanged. The same is true when the fire is modeled as a volumetric heat source: except in the immediate neighborhood of the fire, differences are small, compared to one-step reaction chemistry for combustion, as far as the evaluation of the smoke control system is concerned.

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